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Abstract

We propose a description of product design based on four design spaces. These design spaces correspond to particular representations of the product (need, perception, function and physical representation) which are more or less adapted to the designers and users preoccupations and to the successive stages of the design process. We show that this definition allows the representation of four characteristic design processes, starting from non-explicit needs until the end-products, by specific circulations throughout the design spaces. The most *complete design process*, is composed of five elementary design stages. After a description of different theories and methods useful within the design process, we show how these five design stages may be convenient to naturally locate and connect them.

Keywords: conceptual design, design process, need specification, design assessment, design theories and methodologies

1 Introduction

During the design process, the product is represented in different ways. Starting from an non-explicit and unclear need and ending in precise technical specifications, the product may also be represented by intermediary information, data or objects. These intermediary representations are necessary in the design process since they support the exchanges between the actors of the design. As a particular nature of data implies a particular system of reasoning and often adapted skills and as the design process may be considered as a data transformation process, we have decided to propose a design model based on design spaces characterized by the nature of the product data.

How many conceptual design spaces may be considered? Depending on authors the answer varies from 2 to 4. Most often, three design spaces are only considered: a *need space*, a *functional requirements space* and a *space of variables/principles/behaviors* for the design solutions. This is the case for the mainstream function-structure-behavior theories [1] and this is roughly the case for other theories such as Quality Function Deployment [2] and Axiomatic Design theory [3].

But things are not straightforward from needs to requirements and next to the design solutions, especially when the needs and the functions are not easy to capture, understand, conceptualize and name. For example, practitioners of Functional Analysis often implicitly aggregate both *need* and *functional requirements spaces*. Indeed, they basically adopt the following strong assumptions:

- Needs may easily be comprehended and expressed via a multidisciplinary project team and traditional marketing surveys.
- Needs may be expressed in a set of functions (or functional requirements, i.e. the functions expected from the product). But for mass-products (especially submitted to fashion trends), the customers or the end-users often do not dissect a product into distinct functionalities; their assessment is made on the overall product. That is why one may feel that a given product is likely to be successful without any clear reason, which makes it difficult to formulate functional requirements. In such a case, it might be difficult to assess an a priori satisfaction of the expected product functionalities/services whereas customers' reactions might be a posteriori quantified when confronted to a given set of products.
- A customer is little influenced by the solution of the product implementation (e.g. design principles, materials, manufacturing technologies…).
- A customer expects something precise. But the need may be loose and even actually defined and transformed by the product arrival on the market.

This is why, for a number of products, the semantics of the product with its connotative aspects is preponderant over the services to deliver and the complexity of the user's perception should be carefully studied [4; 5]. The main objective of the present paper is to consider a fourth design space, namely the "*Semantic space*", within the design process.

In addition, a corollary of the question on the number of design spaces to consider is the following: "How many and which design processes should we consider? And, how many and which process stages should we consider they are composed of?"

Authors in Design Engineering present the different major stages of the product design process in somewhat different ways. For example, after Pahl and Beitz [6], four design stages have to occur successively. In the first "*Product Planning and Clarifying the Task*" stage, a raw product orientation is given, relevant information is collected and the list of requirements is established. Next, in the "*Conceptual Design*" stage, an abstraction of the design/redesign problem is carried out to focus on issues of interest, working principles are proposed that lead to the choice of one or more than one combined structures, called concepts. In order to choose or rank concepts, a raw dimensioning is proposed and assessments are made in a more or less subjective way. The third "*Embodiment Design*" stage consists in defining the whole structure of the product, dimensioning it, and assessing it technically and economically. In the fourth "*Detail Design*" stage, the dimensions of the product are toleranced, materials and the specifications of the manufacturing are defined.

Even if pertinent for companies, Pahl and Beitz's model does not appear very adapted for a description of the design process in the case when the user's perception of the product has to be taken into account, or when the semantics of the product with its connotative aspects is preponderant [4; 5; 7]. Indeed, this model does not allow to position different connected theories and methods that can be useful in the design process such as, for example, *Multi-Dimensional Scaling* (MDS) [8], *Semantic Differential Method* [4] or *Conjoint Analysis* [9].

So as to obtain a better mapping of these connected theories and methods and to better consider the product semantics, we propose to consider in section 2 a model of four design spaces: the "Need space", the "Semantic space", the "Functional space" and the "Physical space". In turn, this distinction allows one to consider four design processes, described in section 3: (a) the *Unstructured design*, (b) the *Semantic design*, (c) the *Functional design*, (d) the *Complete design*. One may link our proposition of the *Complete design* process to Pahl and Beitz's well known process. In section 4, we describe the five elementary stages of the *Complete design* process: (1) *Building the Need space*, (2) *Building the Semantic space*, (3) *Building the Functional space*, (4) *Building the Physical space* (or concept generation), (5) *Concept assessment and choice*. As an hint of the ability to locate interesting connected theories and methods, a short state-of-the-art is provided under each of the five stages. A better integration of methods bridging the gaps between the four design spaces would bring advantages in the understanding of needs and the quality of the end result.

2 The four design spaces

When first attempting to characterize customers' needs, marketers, industrial designers and stylists do not only consider product expectations as generated from a functional analysis but also as subjective and cognitive value expectations. These subjective expectations and cognitive values can be expressed by words or images [10]. These semantic tools are more flexible to foresee consumption trends and to state cultural and aesthetic values to give the product its shape and built up its interface. But these semantic dimensions are undoubtedly an interpretation of the crude initial needs of a targeted market segment. Moreover it has been shown in [10] that the perception of the shape of a product is often nothing but a style of design, depending much more on the designer's taste than on real customers' trends. One should consider the design space (*space* in the sense of data characterizing the product) corresponding to the initial crude needs with no or with very little interpretation. We will see further that some methods exist which manage to characterize some aspects of the needs with no interpretation.

Ultimately, our four design spaces are: The "*Need space*", i.e. the space of data representing the needs the potential customers and other product stakeholders (designers, manufacturers, distributors, maintainers, recyclers…) can develop or the constraints they can impose on the product during its lifecycle. In this space, the needs are considered crude, with no a priori interpretation, with no semantic or functional formalization.

- The "Semantic space", i.e. the space of data representing fuzzy feelings, perceptions and expectations on the product (existing or to design) by its language (semantic attributes) or graphical (images) connotations. Giving names implies a choice and a culture-dependent interpretation which could merit to be considered more often in a design process.
- The "*Functional space*", i.e. the space of data representing the product (existing or to design) by its functional characteristics.
- The "*Physical space*", where the product (existing or to design) is characterized by its physical (structural) characteristics, its description, its choices of design principles and its behaviors and states.

The four design spaces are represented in figure 1. On the left-hand side of figure 1 stand the two spaces belonging to the *real world*: the *Need* and the *Physical* spaces. Let us mention that the *Need* *space* represents the crude perception (with no "modeled" interpretation) people have on existing products of a product segment as well as the need for or the necessity to design an ideal product. The *Physical space* includes both the existing products of a product segment and the concept alternatives of the product under design. Conversely, the two spaces that belong to the *model world* appear on the right-hand side: the *Semantic* and the *Functional* spaces. Another partition occurs also with the *Need* and the *Semantic* spaces on the subjective/connotative/fuzzy side and with the *Functional* and the *Physical* spaces on the objective/denotative/explicit/precise/detailed side.

[[insert figure 1]]

We believe that these four *design spaces* are sufficient and well appropriate to locate the various design stages and design processes that are considered in engineering design. The positioning of interesting connected theories and methods relatively to the five elementary design stages that is proposed in section 4 tends to prove it.

3 The four design processes

The four design spaces are convenient to describe four types of design processes (see figure 2).

1. Trying to straightforwardly generate concepts without any analysis, interpretation or modeling of the need has to be considered as a poor design process, since it is known that an incursion into an abstract/model world favors creativity [11]. This process is represented by path (a) in figure 2 and we name it Unstructured design.

2. Interpreting need in a semantic way before generating concepts is well adapted to non-exclusively-technical mass-products where style and connotative aspects are important market arguments. This process is represented by path (b) in figure 2 and we name it *Semantic design*.

3. Interpreting needs in a functional way before generating concepts is well adapted to technical products where style and cultural values are not predominant. This process is represented by path (c) in figure 2 and we name it *Functional design*.

4. Finally, in a general case, we advocate that a representation in both Semantic and Functional ways should concurrently yield a richer concept result. This process is represented by path (d) in figure 2 and we name it *Complete design*.

[[insert figure 2]]

4 The five elementary stages of a complete design and appropriate methods

Let us examine the *Complete design* process in terms of its five successive elementary stages in the light of the four design spaces scheme. For each stage, a short-list of interesting connected (to design) theories and methods is proposed.

4.1 Stage 1: building the need space

How to formalize the need for a product with no or very little assumptions? Two groups of methods are presented further which provide an idea of the size and shape of the need space which takes a diversity of products and consumers into account.

- Many marketing techniques, based on consumer surveys, are used to detect consumption tendencies. The product positioning makes use of perceptual and preference maps. The main methods for preference maps are MDPREF and PREFMAP, well known in the food industry [12].

- To obtain perceptual data about a product segment, *Multi-Dimensional Scaling* (MDS) [8] turned out to be a relevant method. Originally, MDS was used to study the psychological response of subjects to a set of "stimuli". It is a process whereby a distance matrix among a set of stimuli is translated into a representation of these stimuli inside of a perceptual space. For our purpose, it is used to know how a set of products are perceived by subjects. Taking all the possible pairs of stimuli (here pairs of products of the product segment) into account, each subject has to evaluate the degree of similarity of each pair on a qualitative scale (often from 0 to 10). Technically, the MDS technique amounts to locating the products considered as points in a k-dimensional space such that the Euclidean distances between them correspond to the perceived dissimilarities in the input matrix as closely as possible. Dimension k of the need space is the lowest dimension respecting an approximation criterion called *stress,* which represents the "badness of fit". The main advantage of this method is that the tests are based on instinctive dissimilarity assessments, which do not impose any criteria or predefined semantic scale. This method provides a space for the visual representation of the perception of products. It is well suited to study the relationship between products or to perform product clustering.

4.2 Stage 2: building the semantic space

This stage aims at building a semantic understanding of the *need space* and particularly of the customers' space in which the future product will fit. Data on similar existing products (coming from the *Physical space*) and describing how these products are considered by the market segment(s) targeted (coming from the *Need space*) turn out to be essential incoming data. Figure 3 represents these two flows of data by arrows towards the *Semantic space*. Some standard families of methods follow:

- *Semantic differential method* has been formalized by Osgood [4; 5] . This method consists in listing semantic attributes, related to the product to analyze, and carrying out user-tests in which the user must assess the product according to these attributes. The attributes are often defined by a pair of antonymous adjectives which lie at either end of a seven point qualitative scale. A semantic space, Euclidean and multidimensional, is then postulated. *Factor analysis* and *Principal Components Analysis* may be used to reduce the dimension of the space and to find the underlying dimensions. They are used for the analysis of families of products or for the detailed analysis of a product.

- *Sensorial metrology* [13] characterizes qualitatively (which semantic attributes?) and quantitalively sensorial reactions of customers and their expectations for a new product in terms of colors, textures, style, etc, and their satisfactory combinations.

- *Value Marketing approaches* [14] allow to understand the different market segment behaviors and to choose a product design strategy in adequacy with the technical and scientific know-how of the company and with the fashion trends the customers respond to.

- In addition to these methods, Japanese researchers have investigated the customer's feeling under the name *Kansei* Engineering [15], an ergonomic, consumer-oriented technology for product development. This research aims at translating the customer's feeling for the product to the design elements, and proposes to build a database of the consumer's feeling within a systematic framework, which could be updated to adjust the technology to a new *Kansei* trend. *Kansei* Engineering is classified in three types: type I is a category classification in which the image of the product is broken down in a tree structure to get the design elements, type II intends to establish a link between image words (the input) and design elements (outputs) with an approach based on computer aided technique (expert systems), type III is based on a mathematical model..

[[insert figure 3]]

4.3 Stage 3: building the functional space

How can a list of design requirements (see figure 4) be built so as to be as complete and sound as possible? Several families of methods tackle this issue, including:

- *Functional analysis*. So much has already been said about FA. This is undoubtedly the basis of the F-space representation (see [16]). A lifecycle analysis of the services the product has to perform and of the constraints imposed by the environment leads to a set of elementary functions. These functions can conveniently be ordered hierarchically which yields a logical comprehension of the expectations linked to product. Each leaf function of the hierarchy is defined by a set of functional attributes, each of them being in turn defined by a physical unit, an expected level and possible by bounding levels.

- *Value Management* approaches provide additional functions and constraints to the list of requirements built while considering the sole product. For example, considerations of profitability of an existing product family over different market segments and of technical or service improvability (given the company know-how) for a given cost lead to a redesign of the strategy of the offer of the product family in the Volsy's approach [17].

- *Conjoint Analysis* [9] is a more technical and structured marketing approach to generate a functional model. Its aim is to build a model of the customers' needs in terms of "Would a sufficient number of consumers buy such a product configuration?". For that general purpose, methods have been developped for a few decades that are based on very few assumptions but start with customers' surveys determining maximum prices they can afford for a given configuration. Recently, researchers have begun to merge market analysis and the design stages of requirement definition and concept generation [18]. Complete marketing and conceptual design platforms have been proposed in [19; 20]. In both approaches a conjoint analysis, from 20 customers faced with different (textual) functional product descriptions, leads to a model of the customers' preferences. This model at least allows to simulate the market behavior when confronted to a product configuration. But both approaches go further and, in a second stage, a complete space of design configurations is generated (optimal Pareto solutions of a parametric design in [19] and topologically different concepts from a AND/OR structural tree in [20]). Thirdly, costs and performances are assessed for all the design configurations. Fourthly, each design configuration is assessed in the light of a price proposed and of the model of the customer's needs so as to yield an estimation of the demand (out of the 20 customers, how many would buy it?). Ultimately, the demand and cost estimated allow the calculation of the estimated profit. The authors claim that this is *Design for profit*. And is it not the overall objective of an industrial company? But, in our opinion, these two methods present a major drawback: design configurations must be enumerated before knowing which the best list of functional requirements is. This is rather a paradox in design, especially in innovative design, where listing all solutions in advance is a utopian view.

- *Requirements engineering* is quite a new discipline first developed for the purpose of large software projects [21] but presently spreading in the field of design engineering [22]. It tackles the management of requirements along and after a design project in a more systematic way. Typical issues are: capitalization, retrieval and reuse, deployment of requirements along a project, requirements consistency checking.

[[insert figure 4]]

4.4 Stage 4: building the physical space

In the concept generation stage (see figure 5), one has to overcome three issues summarized in three simple questions:

- What should be redesigned from an existing product and where?
  - *Functional analysis*. Using the function/structure model can lead to pinpoint sources of waste or poor quality design [23]. A qualitative overview of the function circulations inside of the structural layout may give some qualitative orientations for improving the structural redundancy or conversely the structural factorization for both maintenance (modularity) and reliability considerations.

- *Axiomatic Design* [3]. Similarly, both independence and information axioms define a clear philosophy to increase the probability to yield satisfactory designs when building the structural layout.
- *Value analysis* [24]. After a cost evaluation of a design solution, the function/structure model can be used to dispatch structural costs into functional costs. Relating the latter ones to the importance of the requirements, sources of waste may be identified. Recently, some works contributed to improve VA indicators [25; 26].

[[insert figure 5]]

- Which new principles should be adopted?
    - *Creativity tools*. [27]
    - *TRIZ* is the major theory to systematically pinpoint design conflicts and to propose leads towards bringing answers (conflict matrix, laws of engineering system evolution, inventive standards, generic inventive ARIZ algorithm) [28; 11; 29].
- How should the most appropriate assembly of components or subsystems be found or synthesized?
    - *Many Artificial Intelligence techniques* can help with the structural synthesis of the concept or at least its sizing. Let us mention those which seem most promising: Case-Based Reasoning or Design [30], Constraint (Logic) Programming [31], Neural Networks [32], Functional Modeling and Reasoning [1].

4.5 Stage 5: concept assessment and choice

We even quicker evoke the huge number of techniques used to evaluate concepts and make a choice (see figure 6), distinguishing the disciplines they come from:

- From design methods
    - *Value analysis or Pahl and Beitz rankings*. Elementary weighted averages of functional performances.
    - *Quality Function Deployment* [2]. For measuring the adequacy between needs (what?) and potential concepts (how?).

[[insert figure 6]]

- Decision-Based Design (DBD) is multi-criteria analysis applied to design, i.e how to choose between decisions (here design concepts or principles) given a set of criteria. Two scientific schools are opposed: on one hand, there is the French constructivist school with Roy [33] that does not suppose any preexisting preference scheme in the decision maker's (designer's) mind before the decision process starts. It led to the:
    - *Series of ELECTRE systems* which attempt to build an ordering of decisions to rule out ambiguities. An example of concept selection is given in [34].

On the other hand, there is the normative American school that considers that a global preference over a decision (vs design) may be expressed as an aggregation of elementary preference contributions (for criteria, vs design attributes/performances in design). Let us mention the major families of methods:

- *Aggregation of preferences* refers to the theoretical issues of this domain [35; 36]. Both Utility theory and weighting methods are subsets of this main domain.

- *Utility theory* is a major technique for aggregating stakeholders' preferences into an overall utility function. Such a method deals with uncertainty of needs/preferences and concept performances and is the basis of a number of platforms of concept selection [37; 38].

- *Pairwise comparisons methods*. Weighting a set of decisions (or designs) with regards to a single criterion is not so simple for the designer because of subjectivity: But it is made still more difficult by the presence of numerous decision makers. Pairwise comparisons methods limit this problem in proceeding by comparing each pair of alternatives. A lot of different methods exist to calculate a set of resulting satisfactory weights. Some permit to consider an uncertainty in the pairwise comparisons and allow for decision makers to have different opinions, but there is no general method. In a recent work, Limayem [39] proposes a method called MCPC to take any uncertainty into account. In addition general consistency indicators are proposed to each decision maker and to the group so as to consciously improve the consistency of decisions [40; 41].

- *Analytic Hierarchy Process* (A.H.P.) [42; 43] and Multiplicative A.H.P. [44; 45] are non trivial hierarchical weighting methods under multiple criteria that make use of pairwise comparisons methods at all levels and which can take uncertainty of judgement into account (fuzzy numbers in [46]).

- *The SPEC method* [47] that one of the authors contributed to develop is, for instance, a method for aggregating preferences mixing weights and fuzzy rules.

* Operational Research (OR):

  - *Goal programming* [48; 49] is an optimization technique that consists in shrinking the distance between the design to be selected and the goals or requirements relative to the ideal design as much as possible.

  - *Pareto-based design selection approaches* [50] state that a weighted sum of preferences is somewhat arbitrary and consequently leads to suboptimal selections in comparison with the conscious design choice for the designer when facing a (often graphical) representation of the subspace of optimal Pareto solutions.

* Statistical Quality Control Methods

  - *Surrogate models or metamodels* [51-53] are techniques for approximating costly design performance evaluations after a design of experiments. Therefore, they are particularly adapted to all the previous DBD and OR methods.

  - *Robust design* may also now efficiently be tackled with performance metamodels [48; 49].

4.6 Matching of our four elementary design stages with Pahl and Beitz's

A matching with Pahl and Beitz's process model [6] follows:

* Our first two stages "Building the Semantic space" and "Building the Functional space" correspond exactly to their first stage "Product Planning and Clarifying the Task".

* Our last two stages "Building the Physical space" and "Concept assessment and choice" can be matched to their "Conceptual design" and "Embodiment design" stages.

5 Conclusion

In this paper, we have proposed a new framework for the description of product design. This framework is based upon the definition of four design spaces, in which particular aspects of the product to be designed can be described. The design spaces, named the Need, the Semantic, the Functional and the Physical spaces, are useful to split up the design process into several stages. The design process can indeed be represented by elementary stages, which establish connections between these design spaces. Thanks to this representation, we have listed four types of design processes and, for the Complete Design process, five elementary design stages. We have next considered several theories and methods useful in the design of products that we categorized according to our elementary design stages.

As a first result, our framework provides a support to visualize how a large number of interesting design-supporting theories and methods are related. Secondly, it suggests ways to connect them, what is not obvious without defining a common structure. The design spaces play in this case the role of the common supports. In particular, it is interesting to find out which methods and theories could be connected in order to:

- better understand the need space,
- express (semantically) needs by perceptions and feelings,
- better specify requirements of a new product, considering both objective and subjective parts,
- assess candidate product concepts.

So as to propose such a new integrated framework, we are currently working to consistently combine the methods of *Multi-Dimensional Scaling* (Stage 1: Building the Need space), *Semantic Differential Method* (Stage 2: Building the Semantic space), *Functional Analysis* (Stage 3: Building the Functional Space), *Pairwise Comparison* and *Analytic Hierarchy Process* (Stage 5: Concept assessment and choice) (cf. [54]). In doing so, we believe that the product semantics is more constantly taken into account throughout the five elementary design stages we described.

Thirdly, this representation could be of interest to identify the lack of integrated design methods, the gap between design spaces, and to suggest research tracks.

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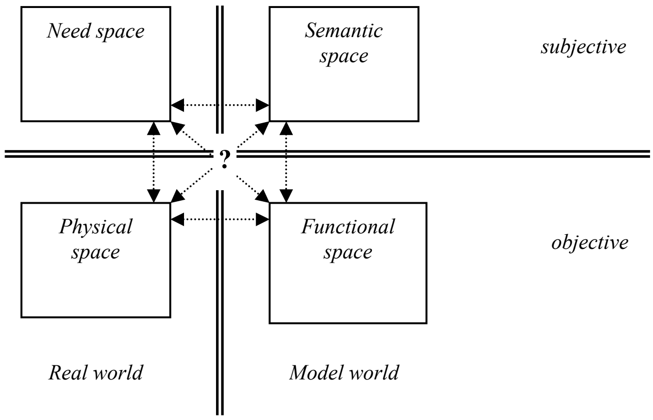

Figure 1: The four design spaces

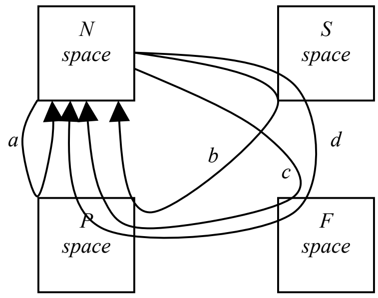

Figure 2: The four types of conceptual design: (a) Unstructured design, (b) Semantic design, (c) Functional design, (d) Complete design

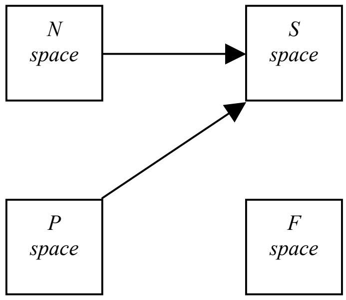

Figure 3: Complete design, stage 1: Building the Semantic space

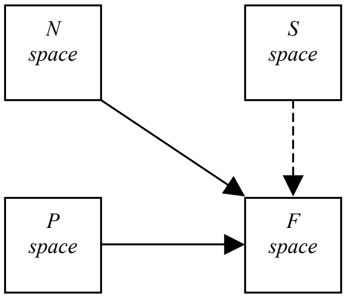

Figure 4: Complete design, stage 2: Building the Functional space

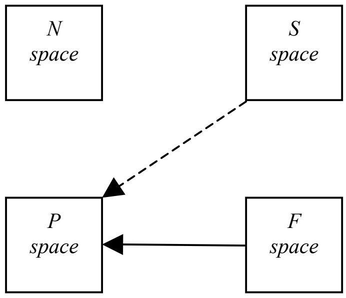

Figure 5: Complete design, stage 3: Building the Physical space

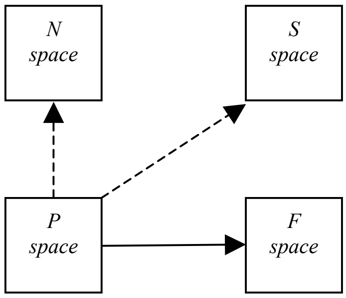

Figure 6: Complete design, stage 4: Concept assessment and choice